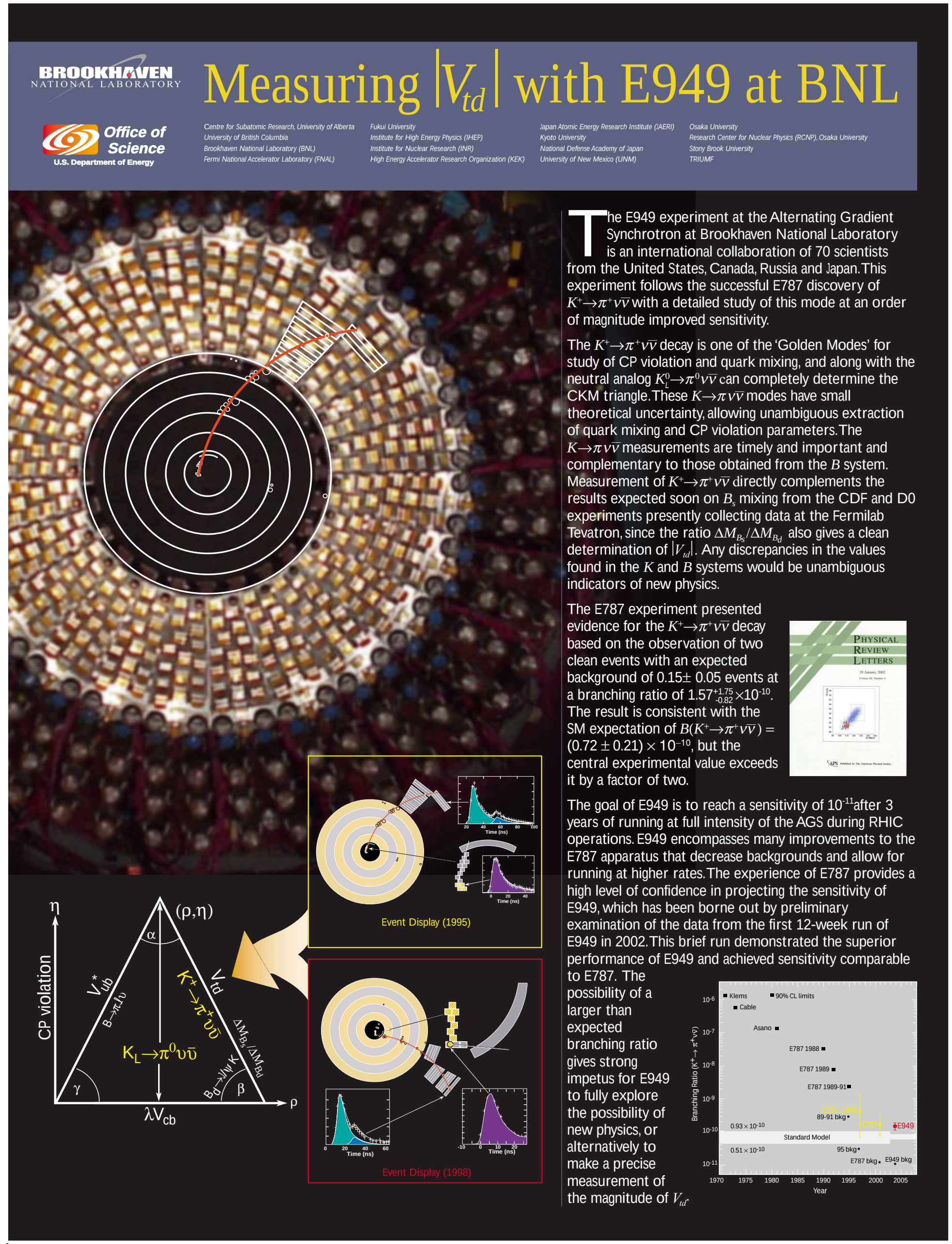
First Results from BNL E949: $K^+ \to \pi^+ \nu \bar{\nu}$

Steve Kettell

BNL

- Overview of E787/E949
- Results
- Conclusions



Workshop on Future Kaon Experiments

BNL, May 13, 2004

E949

An experiment to measure the branching ratio $B(K^+ \to \pi^+ \nu \bar{\nu})$

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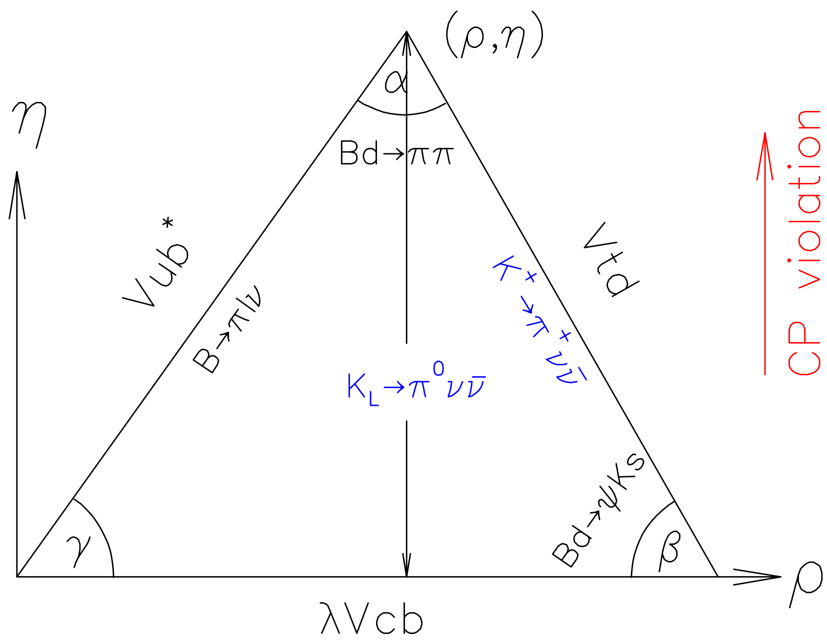
TRIUMF

Students and post-docs in red.

$\sim$70 physicists, plus a lot of hard work from earlier E787 collaborators.

Processes with small theoretical uncertainties



Process	Experiments
$\mathcal{B}(\text{K}^+ \to \pi^+\nu\bar{\nu})$	E787/E949, FNAL-E921
$\mathcal{B}(\text{K}^0_\text{L} \to \pi^0\nu\bar{\nu})$	KOPIO, E391a
$\mathcal{A}(B \to J/\psi\text{K}^0_\text{S})$	BaBar, Belle

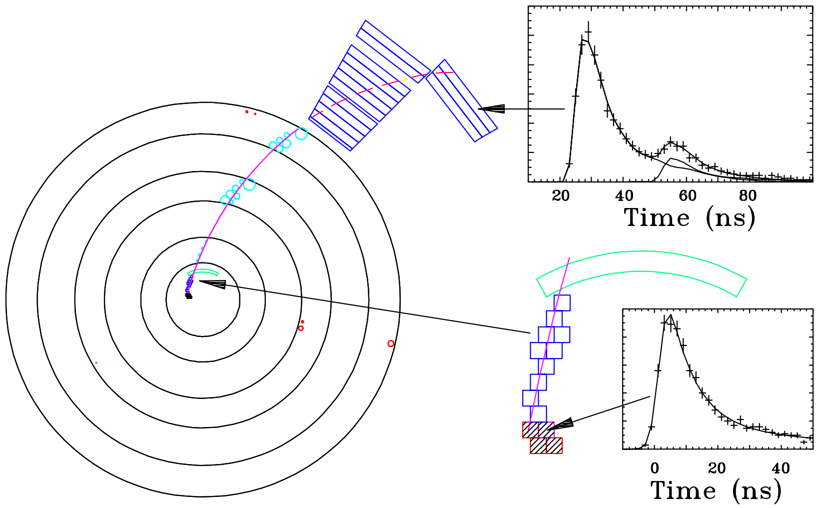
CP violating decay rate asymmetry

$\Delta M_{B_s}/\Delta M_{B_d}$	CDF, D0, LHCb, BTeV

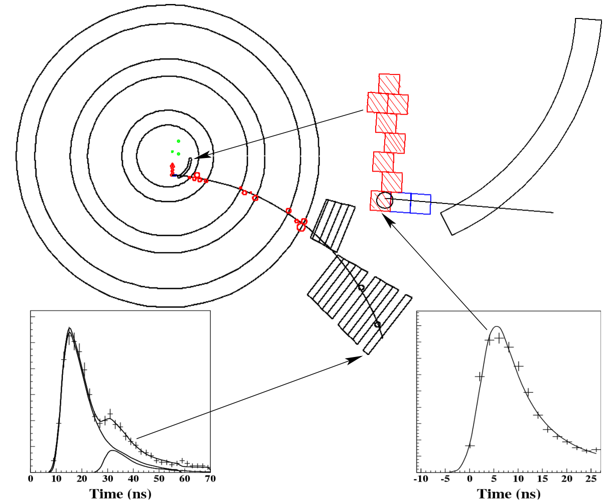
ratio of mixing frequencies of B_s and B_d mesons

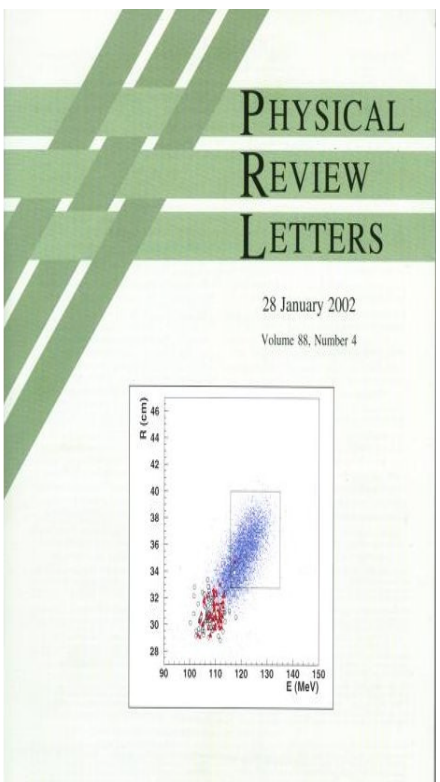
- Comparison of $|V_{td}|$ from $\mathcal{B}(\text{K}^+ \to \pi^+\nu\bar{\nu})$ and from $\Delta M_{B_s}/\Delta M_{B_d}$ provides an important test of the SM.
- Comparison of $\sin 2\beta$ from $\mathcal{B}(\text{K}^0_\text{L} \to \pi^0\nu\bar{\nu})/\ \mathcal{B}(\text{K}^+ \to \pi^+\nu\bar{\nu})$ and from $\mathcal{A}(B \to J/\psi\text{K}^0_\text{S})$ is perhaps **the** definitive test of the SM picture of CP violation.

Candidate E787A



Candidate E787C





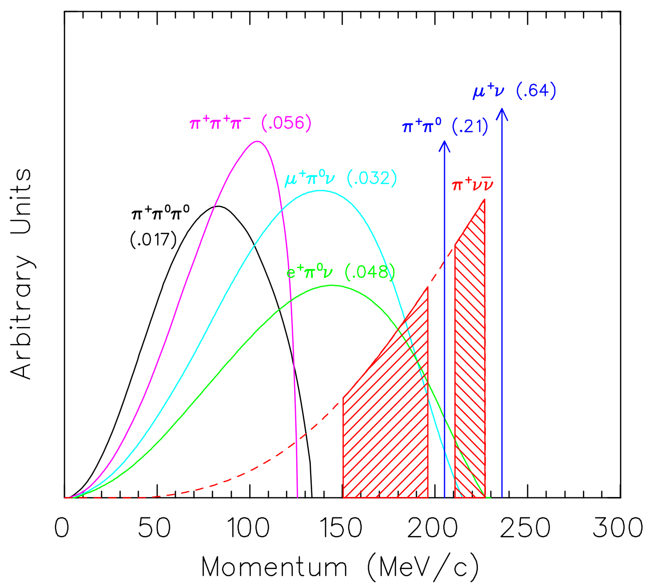
	"PNN2"	**"PNN1"**
P_π (MeV/c)	[140,195]	[211,229]
Years	1996-97	1995-98
Stopped K$^+$	1.7×10^{12}	5.9×10^{12}
Sensitivity (S.E.S.)	6.9×10^{-10}	0.83×10^{-10}
Candidates	1	2
Background	1.22 ± 0.24	0.15 ± 0.05
$\mathcal{B}(K^+ \to \pi^+ \nu \bar{\nu})$	$< 22 \times 10^{-10}$	$(1.57^{+1.75}_{-0.82}) \times 10^{-10}$

PNN1: PRL **88**, 041803 (2002).

PNN2: limit is combined from 1996 [PL **B537**, 211 (2002)] and 1997 [hep-ex/0403034] data. (1997 acceptance 1.27× 1996)

Experimental Considerations for $K^+ \to \pi^+ \nu \overline{\nu}$

- 3-body decay with 2 missing particles $\Rightarrow 0 \leq P_{\pi+} \leq 227 \mathrm{MeV}/c$ ...and $\mathcal{B} < 10^{-10}$
- Must veto each extra particle to $\leq 10^{-3}$
- Particle identification (PID) is essential.
- Redundant precise kinematic measurements.
- Supress backgrounds by 10^{11}



$P_{\pi+}$ in K$^+$ rest frame

Process	$\mathcal{B}$	PID	veto	kin.	time
$K^+ \to \pi^+\pi^0$ ($K_{\pi 2}$)	0.21	-	$\surd\ \surd$	$\surd$	-
$K^+ \to \mu^+\nu$ ($K_{\mu 2}$)	0.63	$\surd$	-	$\surd$	-
$K^+ \to \mu^+\nu\gamma$	0.005	$\surd$	$\surd$	-	-
$K^+ \to \pi^0\mu^+\nu$	0.032	$\surd$	$\surd\ \surd$	-	-
$K^+ \to \pi^0 e^+\nu$	0.048	$\surd$	$\surd\ \surd$	-	-
$K^+ \to \pi^+\pi^-\pi^+$	0.056	-	$\surd$	$\surd\ \surd$	-
π^+ scatter	-	$\surd$	-	-	$\surd$
$K^+ n \to K_L$ p; $K_L \to \pi^+\ell^-\nu$	-	-	$\surd$	-	$\surd$

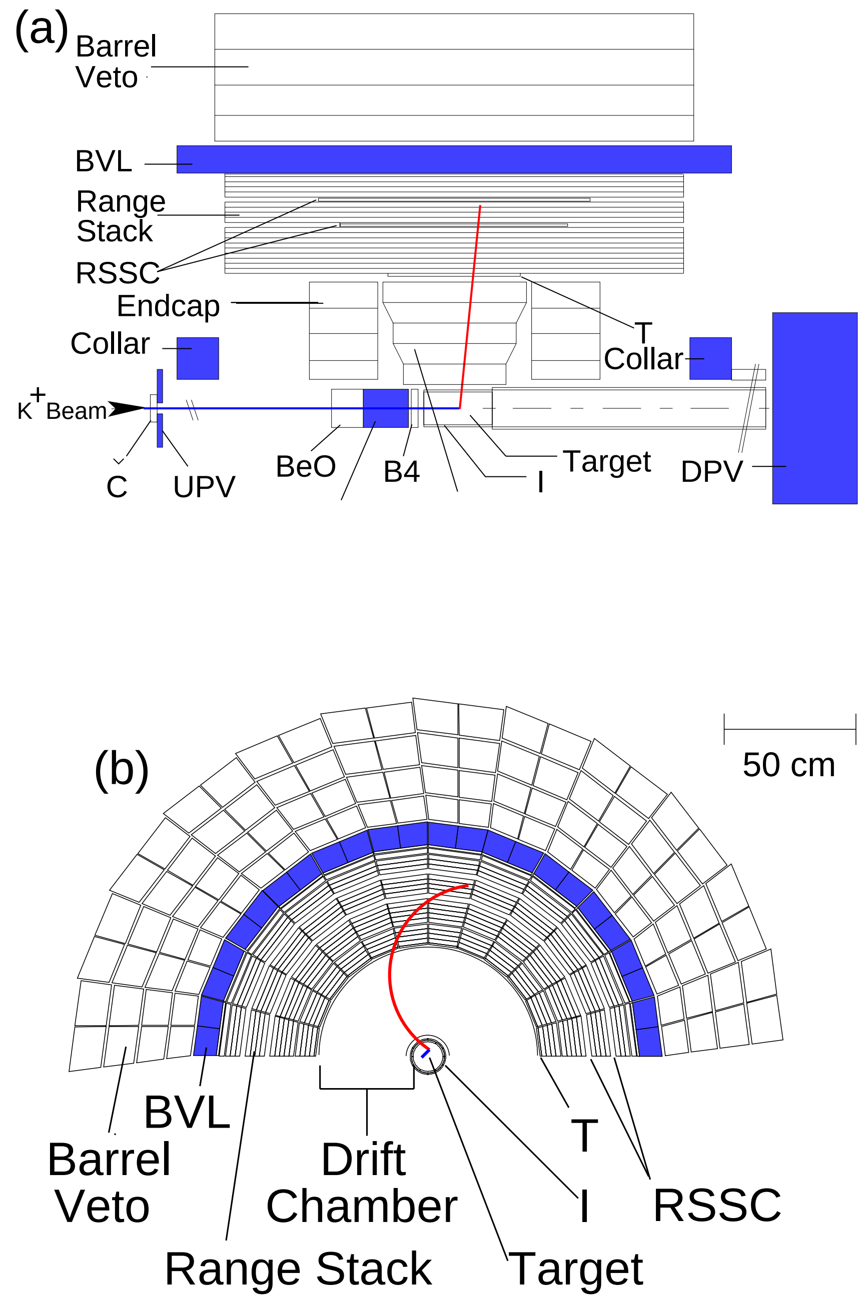
"kin." = kinematic suppression

"PID" = includes π/μ and K/π discrimination

$\mathcal{B}(K^+ \to \pi^+\nu\overline{\nu}) = 0.77 \times 10^{-10}$

E949 method

- $\sim$ 700 MeV/c K$^+$ beam
- Stop K$^+$ in scint. fiber target
- Wait at least 2 ns for K$^+$ decay
- Measure P in drift chamber
- Measure range R and energy E in target and range stack (RS)
- Stop π^+ in range stack
- Observe $\pi^+ \rightarrow \mu^+ \rightarrow e^+$ in RS
- Veto photons, charged tracks
- **New/upgraded detector elements**



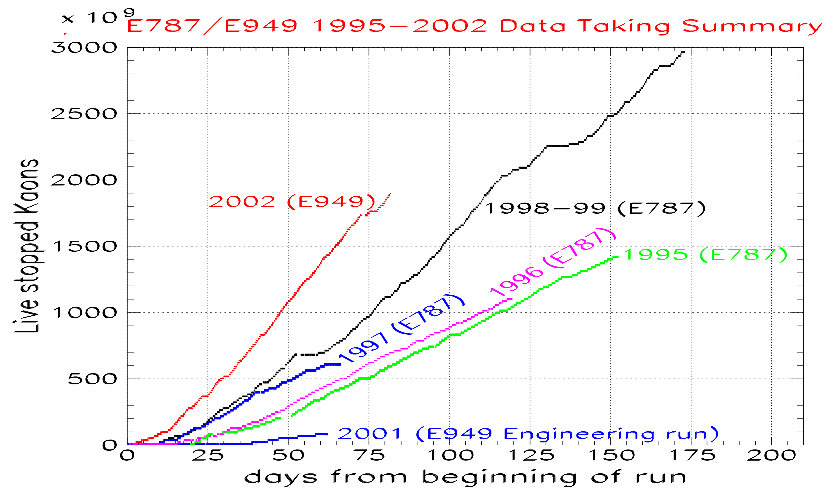
E949 Upgrades

Upgrades to E787:

- More protons from AGS
- Improved photon veto

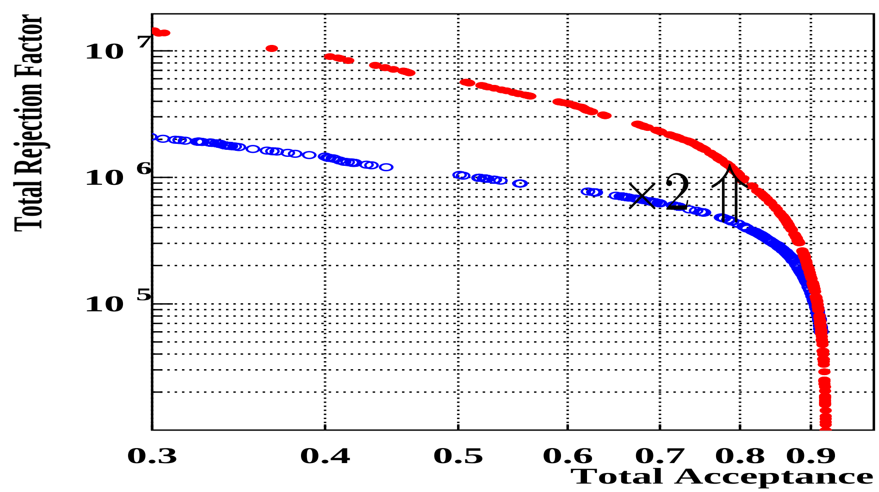
$\rightarrow$ Lower phase space now accessible

- Improved tracking and kinematic resolution
- Improved trigger/DAQ — reduce deadtime and allow high rate operation
- Improved beam system



Not optimal in 2002:

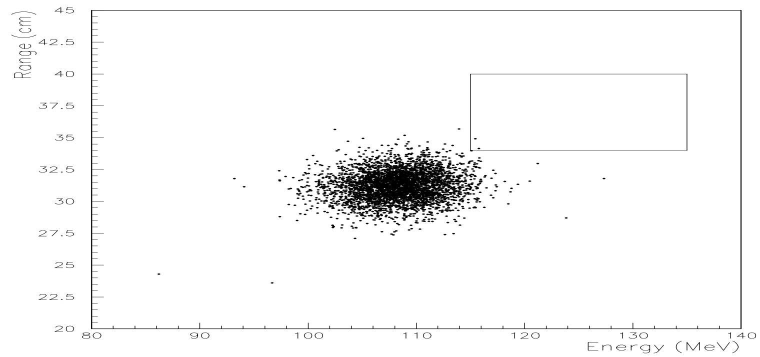
1. Duty factor.
2. Proton energy.
3. K/π separation, K^+ flux



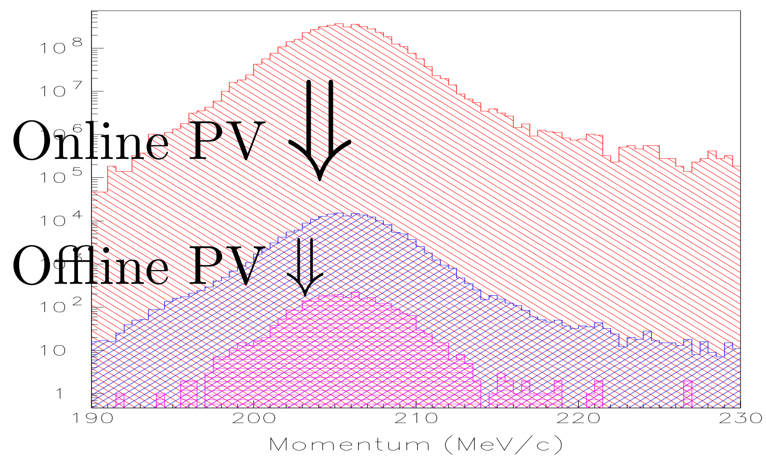
Background **Rejection** as a function of $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ signal **Acceptance** for the photon veto cut for E787 and E949.

E787 and E949 analysis strategy

- *A priori* identification of background sources.
- Suppress each background source with at least two independent cuts.
- Backgrounds cannot be reliably simulated: measure with data by inverting cuts and measuring rejection taking any (small) correlations into account.
- To avoid bias, set cuts using 1/3 of data, then measure backgrounds with remaining 2/3 sample.
- Verify background estimates by loosening cuts and comparing observed and predicted rates.
- Use MC to measure geometrical acceptance for $K^+ \to \pi^+\nu\bar{\nu}$. Verify by measuring $\mathcal{B}(K^+ \to \pi^+\pi^0)$.
- "Blind" analysis. Don't examine signal region until all backgrounds verified.



Select photons, measure rejection of kinematic cuts (P, R, E).



Select $K^+ \to \pi^+\pi^0$ kinematically, measure rejection of photon veto.

Verify background prediction by loosening cuts

Relax cut to reduce rejection by $\times 10$. New, larger region should have $10\times$ background of signal box.

	PV×KIN	10×10	20×20	20×50	50×50	50×100
$K_{\pi2}$	Observed	3	4	9	22	53
	Predicted	1.1	4.9	12.4	31.1	62.4
	TD×KIN	10×10	20×20	50×50	80×50	120×50
$K_{\mu2}$	Observed	0	1	12	16	25
	Predicted	0.35	1.4	9.1	14.5	21.8
	TD×KIN	10×10	20×20	50×20	80×20	80×40
$K_{\mu m}$	Observed	1	1	4	5	11
	Predicted	0.31	1.3	3.2	5.2	10.4

$K_{\mu m} \equiv K^+ \to \mu^+\nu\gamma$, $K^+ \to \pi^0\mu^+\nu$ and $K^+ \to \pi^+\pi^0$; $\pi^+ \to \mu^+\nu$

TD$\equiv \pi \to \mu \to e$ identification, PV≡Photon Veto rej., KIN≡ kinematic rej. $M \times N \equiv$ reduction in rejection with respect to signal region ($\equiv 1\times1$)

Quantify consistency: Fit $N_{\mathrm{obs}} = cN_{\mathrm{pred}}$ and expect $c = 1$.

Background	c	χ^2 Probability	Total background
$K_{\pi2}$	$0.85^{+0.12}_{-0.11}$	0.17	0.216 ± 0.023
$K_{\mu2}$	$1.15^{+0.25}_{-0.21}$	0.67	0.044 ± 0.005
$K_{\mu m}$	$1.06^{+0.35}_{-0.29}$	0.40	0.024 ± 0.010

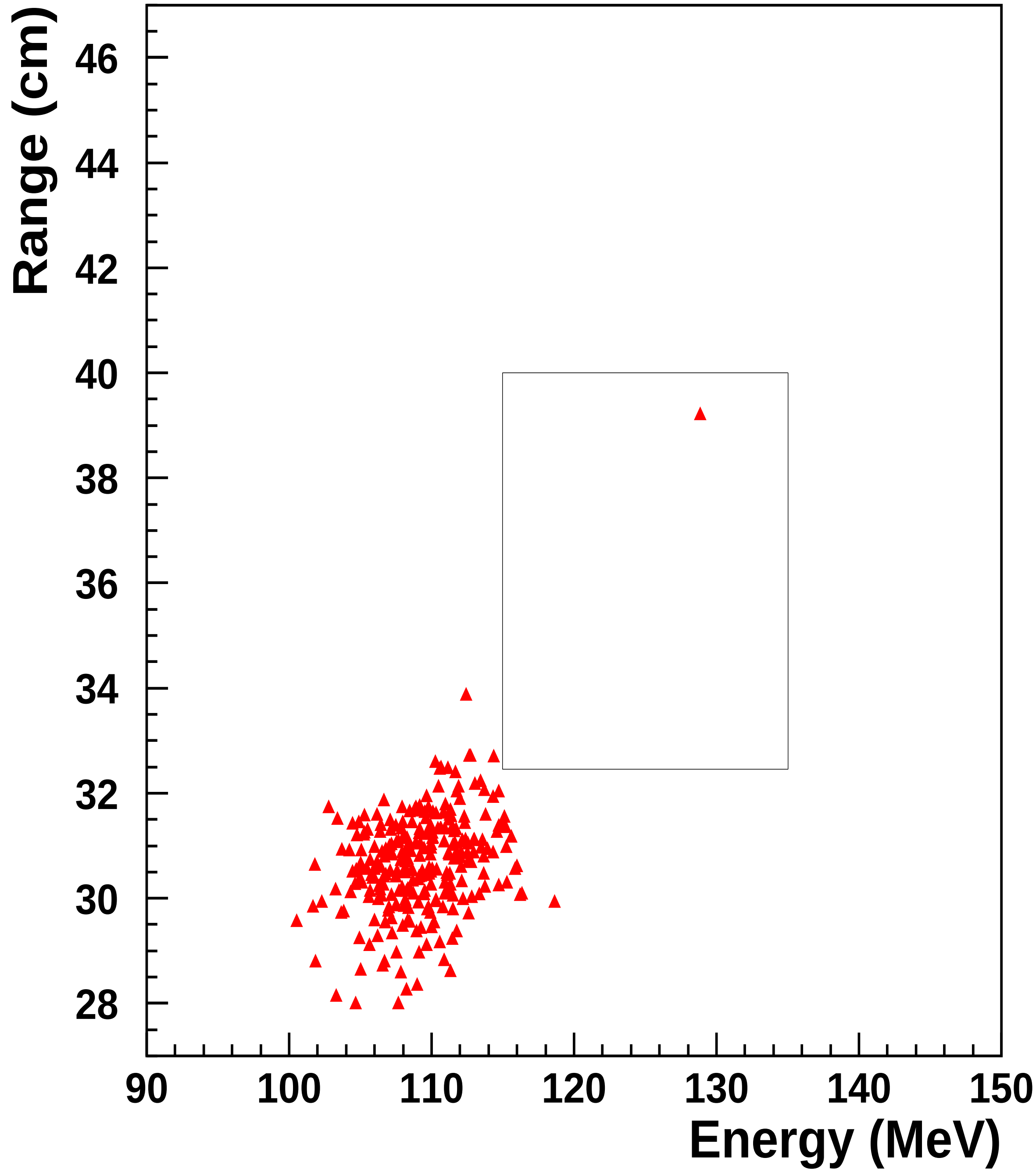
Opening the box

Range (cm) *vs* Energy (MeV) for E949 data after all other cuts applied.

Solid line shows signal region.

Single candidate found.

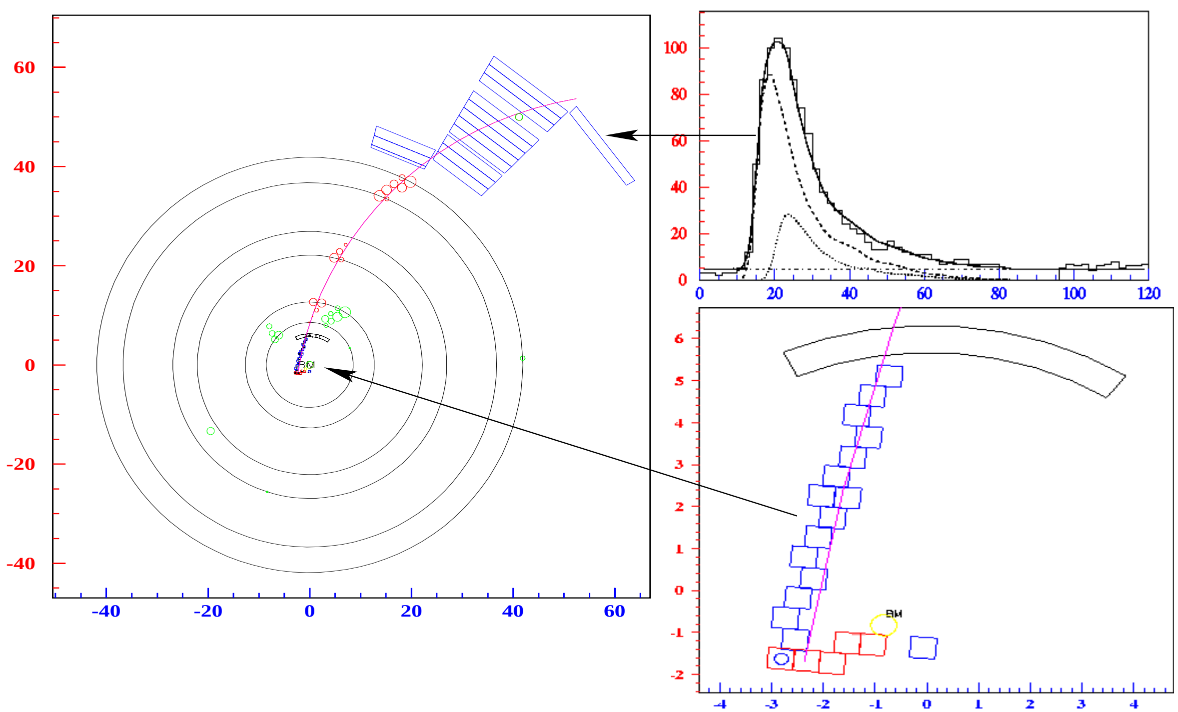
Cluster near 110 MeV is unvetoed $K^+ \rightarrow \pi^+\pi^0$.



Event characteristics

Date of event	April 2, 2002
Run/spill/event	48634/335/76046
Time in spill	1.27s
Kaon energy in target	79.7 MeV
Kaon time in target (t_K)	0.6 ns
z of kaon decay vertex	8.9 cm
(x, y) of kaon decay vertex	(-2.8, -1.6) cm
Pion energy in target	20.8 MeV
Pion range in target	7.6 cm
Pion time in target (t_π)	4.9 ns

Pion time in IC (ictime)	3.8 ns
$\cos\theta$ of the pion track	-0.24
ϕ_0 of the pion track	1.42
Pion momentum	227.3 MeV/c
Pion range	39.2 cm
Pion kinetic energy	128.9 MeV
RS stopping sector/layer	3/14
Pion lifetime	6.2 ns
Muon energy	3.7 MeV
Muon lifetime	1370.53 ns
Range-momentum	0.63



Is this event background?

How likely is it that the candidate is due to known background?

Question: Suppose we do 100 experiments, how many will have a candidate from a known background source that is as signal-like or more signal-like than the observed candidate?

Answer: ~ 7

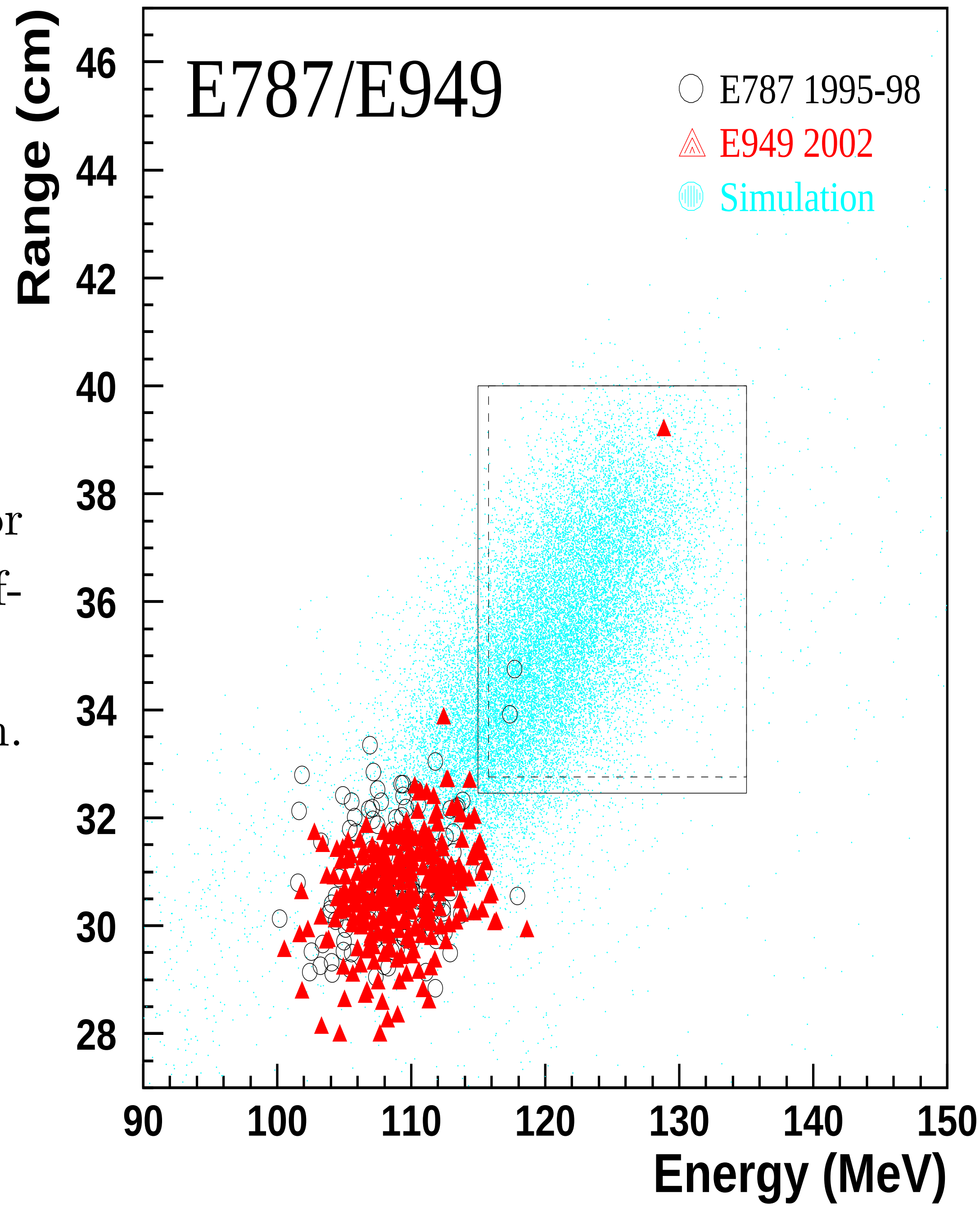
The sum of background in all cells with s_i/b_i greater or equal to the cell containing the observed candidate is 0.077. The probability that 0.077 could produce one or more events is 0.074 ($\sim 7/100$).

The E949 candidate is more likely to be due to background than the two E787 candidates.

Candidate	E787A	E787C	E949A
Probability	0.006	0.02	0.07

Combined E787/E949

Range (cm) *vs.* Energy (MeV) for combined E787 and E949 data after all other cuts applied. Dashed line is E787 signal region. Solid line is E949 signal region.



1995–2002: $\mathcal{B}(K^+ \to \pi^+ \nu\bar{\nu}) = 1.47^{+1.30}_{-0.89} \times 10^{-10}$

	E787		E949
Stopped K$^+$ (N_K)	5.9×10^{12}		1.8×10^{12}
Total Acceptance	0.0020 ± 0.0002		0.0022 ± 0.0002
S.E.S.	0.8×10^{-10}		2.6×10^{-10}
Total Background	0.14 ± 0.05		0.30 ± 0.03
Candidate	E787A	E787C	E949A
S_i/b_i	50	7	0.9
$W_i \equiv \frac{S_i}{S_i+b_i}$	0.98	0.88	0.48

b_i = background of cell containing candidate

$S_i \equiv \mathcal{B} A_i N_K$ = signal for cell containing candidate

$A_i \equiv$ acceptance

$\mathcal{B}$ = measured central value of K$^+ \to \pi^+\nu\bar{\nu}$ branching fraction

$W_i \equiv S_i/(S_i + b_i)$ = *a posteriori* event weight

Combined E787 and E949 results for $\mathcal{B}(K^+ \to \pi^+ \nu\bar{\nu})$

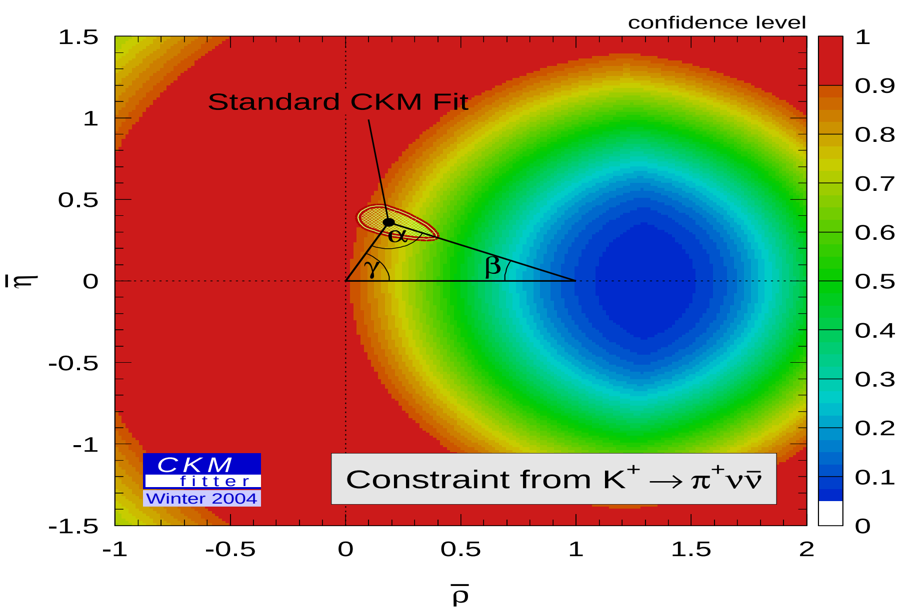
$$\mathcal{B}(K^+ \to \pi^+ \nu\overline{\nu}) = (1.47^{+1.30}_{-0.89}) \times 10^{-10} \quad \text{(68\% CL interval)}$$

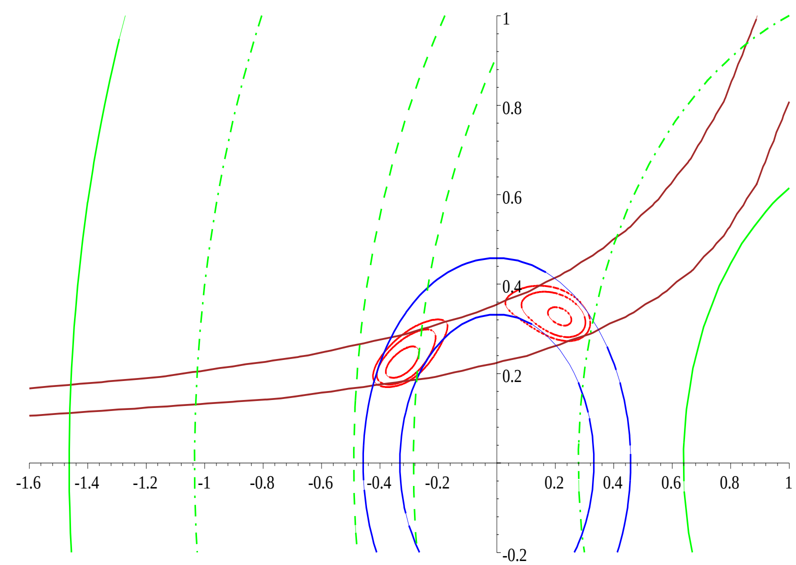
$$\mathcal{B}(K^+ \to \pi^+ \nu\overline{\nu}) > 0.42 \times 10^{-10} \text{ at 90\% CL.}$$

$$\mathcal{B}(K^+ \to \pi^+ \nu\overline{\nu}) < 3.22 \times 10^{-10} \text{ at 90\% CL.}$$

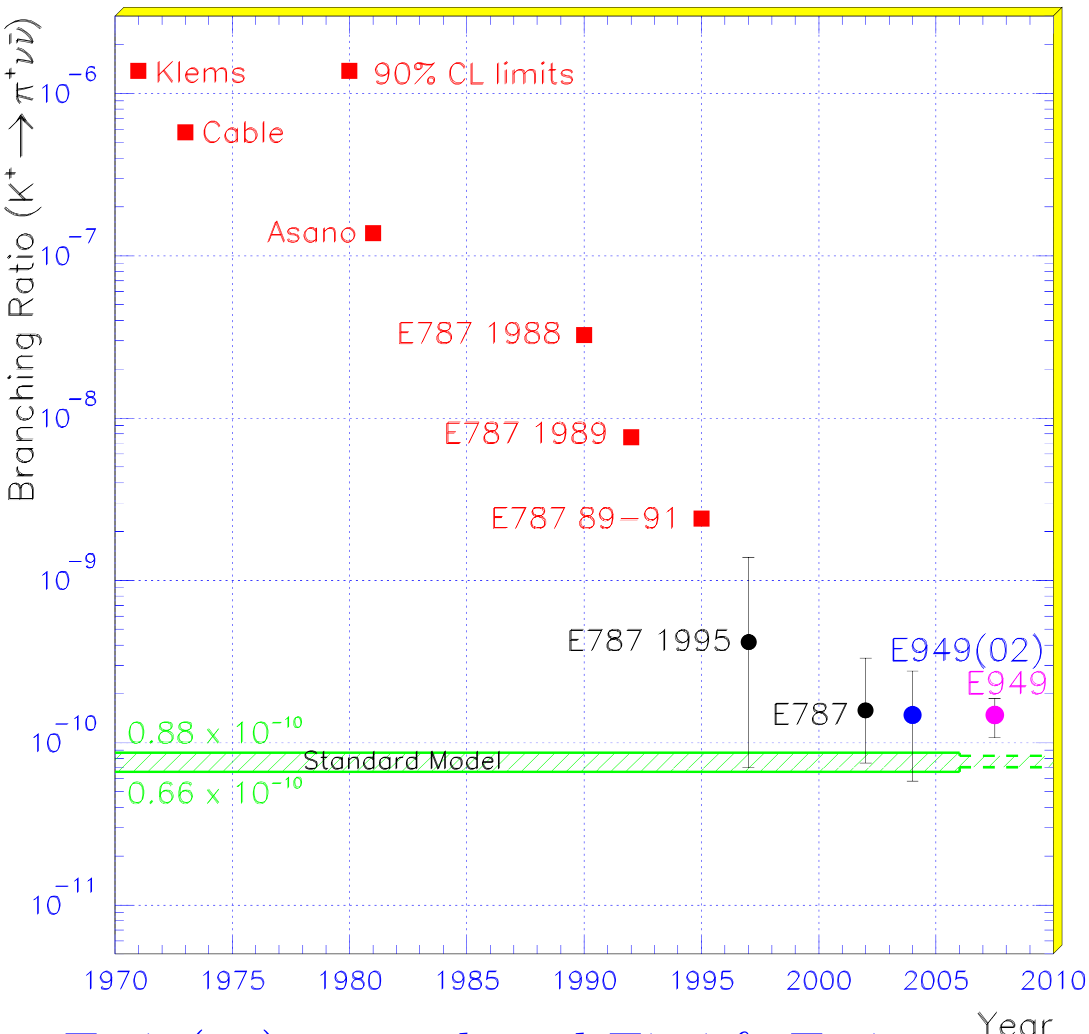
SM: $\mathcal{B}(K^+ \to \pi^+ \nu\bar{\nu}) = (0.77 \pm 0.11) \times 10^{-10}$ [B&B NP**B548**,309(1999)]

$\mathcal{B}(K_L \to \pi^\circ \nu\overline{\nu}) < 1.4 \times 10^{-9}$ at 90% CL. [Grossman&Nir PL**B398**,163(1997)]



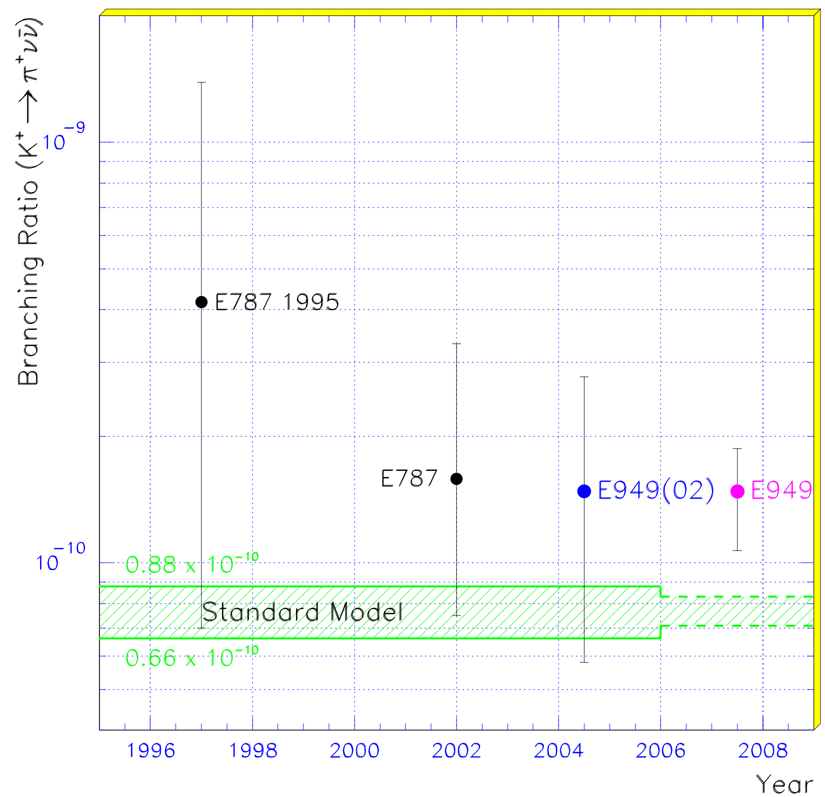


Progress in $K^+ \to \pi^+ \nu \bar{\nu}$



E949(02) = combined E787& E949.

E949 projection with full running period.



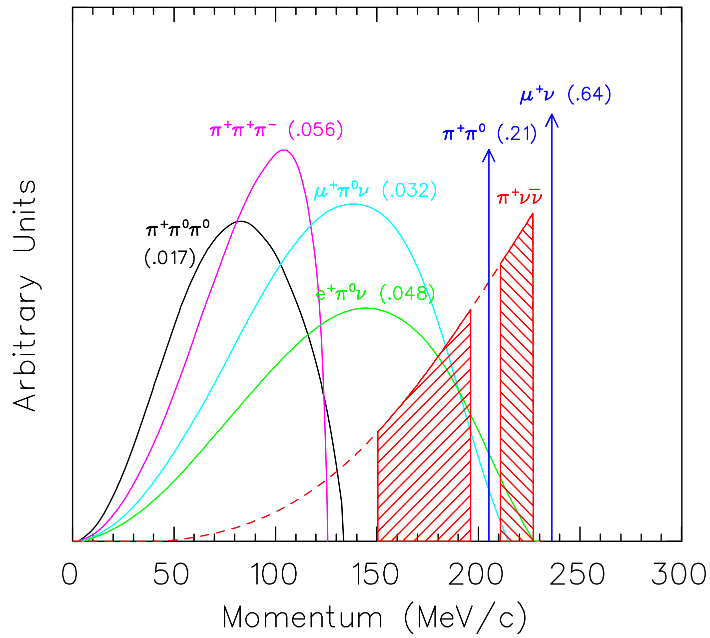
Narrowing of "SM prediction" assumes measurement of B_s mixing consistent with prediction.

Very interesting .... so What Next?

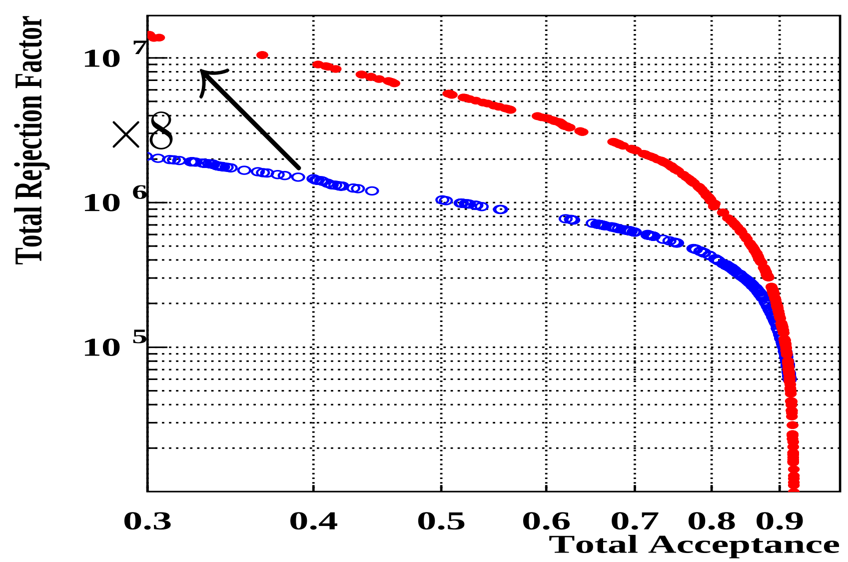
- A 3^{rd} $K^+ \to \pi^+ \nu\overline{\nu}$ event has been observed. The BR remains 2×SM.
  $\Longrightarrow$ **More data is needed.**
- E949 is analyzing more data (PNN2, phase space below the $K^+ \to \pi^+ \pi^\circ$ peak)
- More E949 running? Finish the experiment...
- Next generation $K^+ \to \pi^+ \nu\overline{\nu}$ experiment?

PNN2: $K^+ \rightarrow \pi^+\nu\bar{\nu}$ below $K^+ \rightarrow \pi^+\pi^0$ peak

- More phase space than PNN1
- Less loss due to π^+N interactions
- $P(\pi^+) = (140{,}195)$ MeV/c probes more of $K^+ \rightarrow \pi^+\nu\bar{\nu}$ spectrum
- Main background mechanism is $K^+ \rightarrow \pi^+\pi^0$ followed by π^+ scatter in target.



- E787: PNN2/PNN1 acceptance $\sim \frac{1}{2}$
- E949 goal: PNN2 sensitivity equal to PNN1 with S/B = 1. (This implies $\times 2$ increase in acceptance and $\times 5$ increase in background rejection.)
- Upgraded photon veto.
- Improved algorithms to identify $K^+ \rightarrow \pi^+\pi^0$ followed by π^+ scatter in target.



What about more running of E949

• BNL and FNAL developed a plan to fully exploit the 'kaon' component of flavor physics and to capitalize on the observation of $K^+ \to \pi^+ \nu\bar{\nu}$ by E787. This plan included E949, designed to observe 10 SM events, and CKM, using a new decay-in-flight technique with higher rate capability, designed to observe 100 SM events.

• E949 was evaluated as 'must do' by the BNL PAC and approved by BNL in 1998; CKM was given scientific approval by FNAL in 2001.

• This plan was endorsed by DOE-HEP and E949 was approved by DOE in August 1999 to run for 60 weeks, concurrent with RHIC operation, over three years (FY01–03).

• HEP operations at AGS halted by DOE after 12 weeks of successfull running. Upgrades performed as predicted.

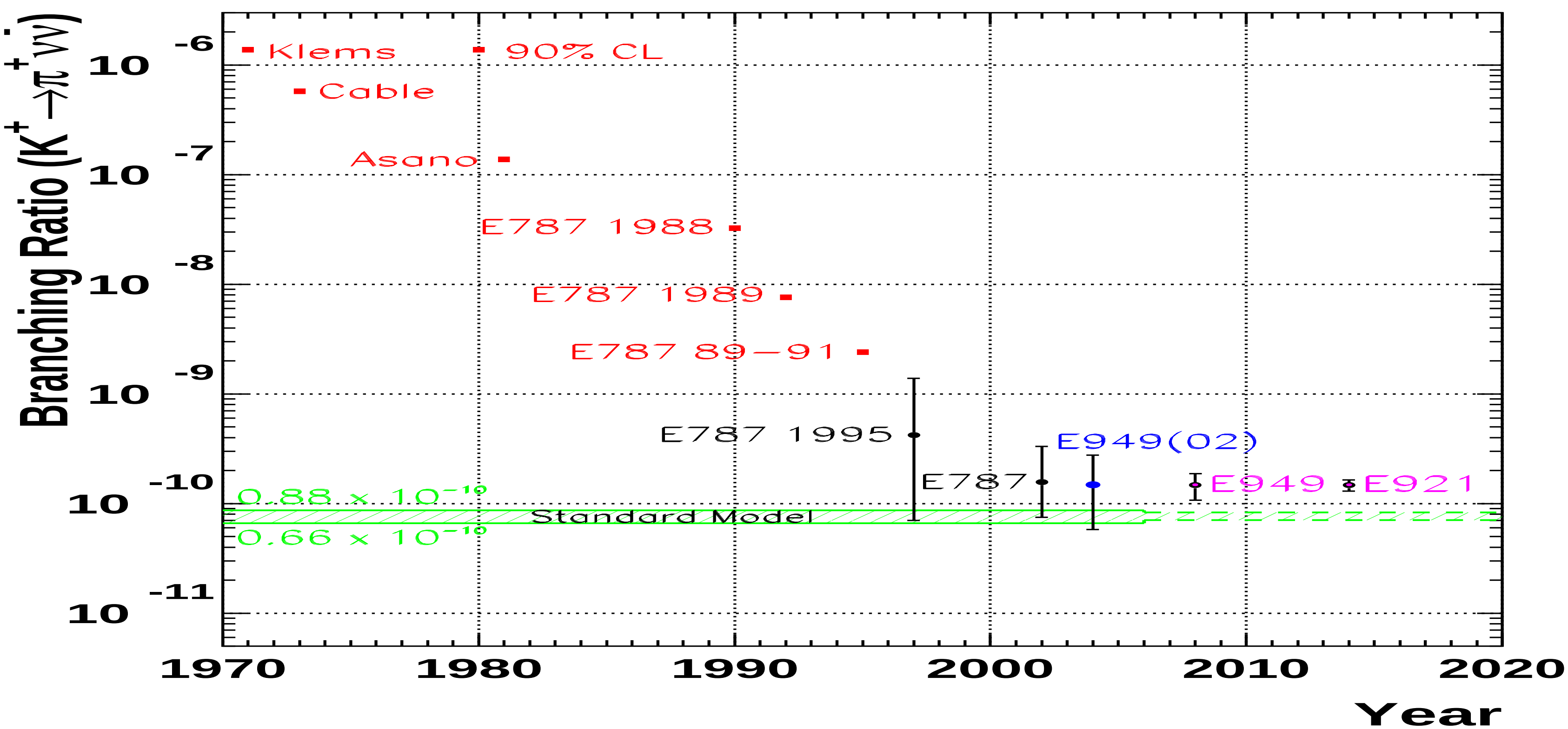
• A proposal to continue running E949 has been submitted to the National Science Foundation

The future of $\mathrm{K}^+ \rightarrow \pi^+\nu\bar{\nu}$

- E949 Analysis of $\mathrm{K}^+ \rightarrow \pi^+\nu\bar{\nu}$ for $P(\pi^+) < 195$ MeV/c is in progress.

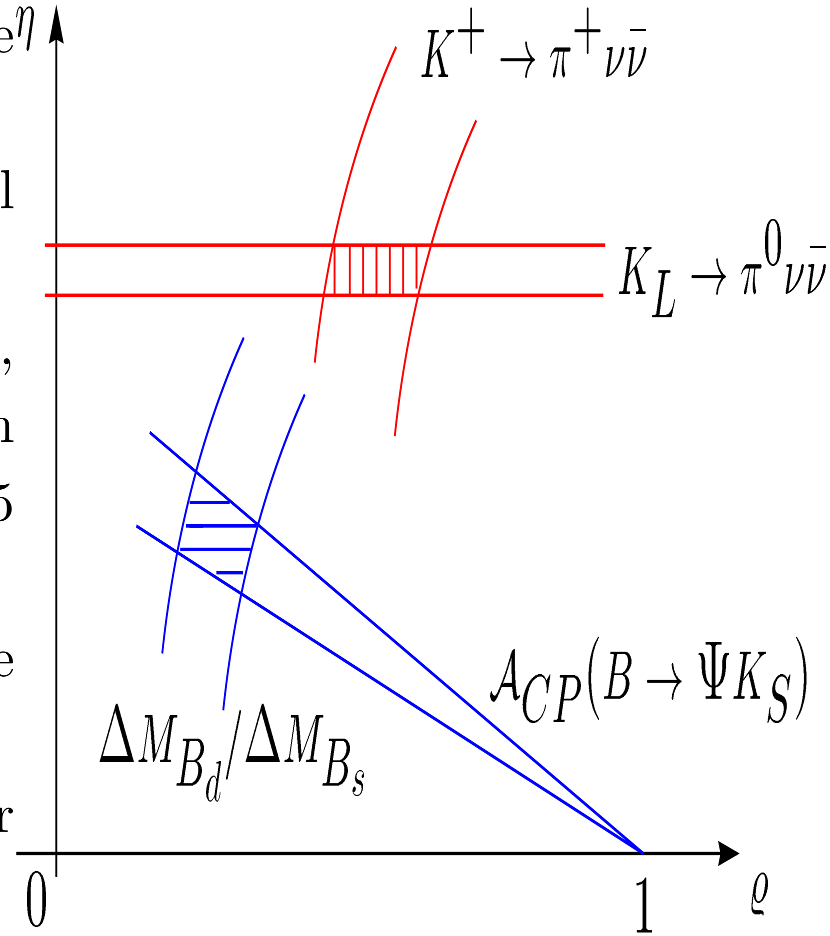
- The E949 detector and collaboration are ready to complete the experiment and are awaiting funding.

- Future $\mathrm{K}^+ \rightarrow \pi^+\nu\bar{\nu}$ experiments: stopped K^+ at J-PARC? or decay-in-flight experiments at FNAL or CERN?



Conclusions

- Upgrades of E787 to create E949 were successful.
- E949 has observed an additional $K^+ \to \pi^+ \nu\bar{\nu}$ candidate: $\mathcal{B}(K^+ \to \pi^+\nu\bar{\nu}) = (1.47^{+1.30}_{-0.89}) \times 10^{-10}$, twice the SM prediction. (Consistent with the SM and similarly consistent with 3.5 times the SM.)
- The detector and collaboration are ready to complete the experiment.
- E949 analysis of $K^+ \to \pi^+\nu\bar{\nu}$ for $P(\pi^+) < 195$ MeV/c is in progress.



Critical tests of the Standard Model:

- **Overconstrain β from $B_d^\circ \to \psi K_S^\circ$ and $K_L^\circ \to \pi^\circ\nu\bar{\nu}$ / $K^+ \to \pi^+\nu\bar{\nu}$**
- **Overconstrain $|V_{td}|$ from $\Delta M_{B_s}/\Delta M_{B_d}$ and $K^+ \to \pi^+\nu\bar{\nu}$**